Generating Mechanism of Low-frequency Stick-slip Motion and Creep Groan Map (低周波型スティックスリップの発生機構とクリープグローンマップに関する研究)

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論文内容要旨

Chapter 1 Introduction

Creep groan is a low-frequency stick-slip motion usually found in automotive braking system and included in one of automotive noise, vibration, and harshness (NVH) problems. The low frequency stick-slip motion (20-400 Hz) originates at the interface between brake pads and rotor as the result of simultaneous application of engine torque and slow release of brake pressure. The vibration occurs at start of sliding at very low sliding velocity (about 10 mm/s) and involves the vibration of the suspension. Brake creep groan is usually related to two parameters, namely difference between static and kinetic coefficient of friction, $\Delta\mu$ (μ_s - μ_k), and stiffness of the strut, a component of the suspension system. However, $\Delta\mu$ is not a controllable parameter and the use of damping on the strut have not been effective in eliminating brake creep groan. In order to provide a solution to the problem, a fundamental research is required. It is to obtain a fundamental understanding on the relationship among various parameters such as contact condition, material properties, and stiffness of the structure to creep groan generation so that a design concept for avoiding brake creep groan can be obtained.

In this study, a simple yet effective experimental model has been designed and adopted to investigate the fundamental generating mechanism of low-frequency stick-slip of creep groan. The caliper-slider experimental model is designed based on principle operation behind the brake system and has the ability to produce stick-slip motion quantitatively similar to creep groan on real brake system. The main objective of this work is to provide a new design concept for avoiding the generation of creep groan. This design concept is presented in a form of map that shows the necessary condition for creep groan generation on the caliper-slider experimental model. It is expected that the design concept can be applicable to real system as well.

Chapter 2 Design of Caliper-slider Experimental Model

To date, there has been no experimental model proposed or used in investigation of brake creep groan. For the purpose of this study, a novel experimental model has been designed and adopted. The simple-yet-effective experimental model is designed based on the principle operation behind a brake system and possesses four most important components necessary to mimic the behavior of a brake system in regards to brake creep groan generation. These components are caliper, slider, arm, and contact interfaces. The so-called caliper-slider experimental model is shown in Fig. 1. The caliper is made to resemble the caliper of the brake system on which two pins are installed. The pins function like those of brake pads. The slider is a component made to represent the rotor of a brake system and the arm is the component that represents the stiffness of the system analog to that of the strut in a McPherson brake suspension system.

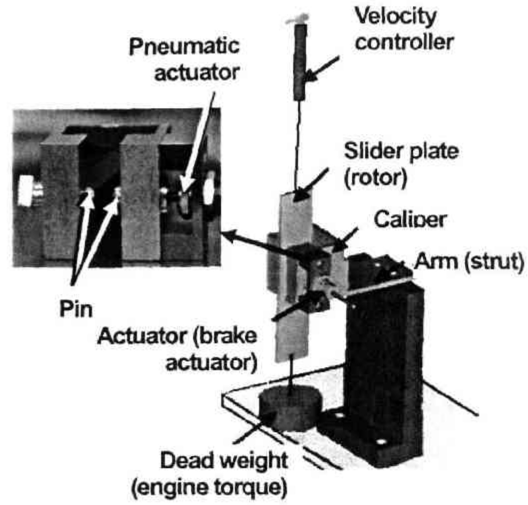

Fig. 1 Caliper-slider experimental

The usefulness of the experimental model is shown by its ability to produce low-frequency stick-slip motion which is quantitatively similar to brake creep groan using similar material combinations used in real brake system, i.e. Carbon steel (S45C) and brake lining materials. The reproduced stick-slip motion has principle frequency of 26 Hz, which is comparable to 42 Hz of brake creep groan stick-slip frequency obtained from a car test.

The main advantages of the experimental model are as follows:

a. Simple and flexible. The components of the model are relatively easy to fabricate. Therefore, effect of various parameters such as contact roughness, material combinations at contact interfaces, and stiffness of the arm can be investigated.
b. Sensitive. The model is sensitive to creep groan generation and that small change in parameter's value can produce significant change in characteristic of generated stick-slip motion.
c. Using the experimental model, it becomes possible to investigate the effects of various parameters, particularly those related to contact interfaces such as surface roughness. This parameter is believed to be important for the generation brake creep groan but the effect is still not clarified yet.

Advantages possessed by this caliper-slider experimental model make it a suitable tool for obtaining a fundamental understanding for generating mechanism of stick-slip motion such as creep groan in brake system.

Chapter 3 Low-frequency Stick-slip Motion Generated on the Caliper-slider Experimental Model

Whilst force, material properties, and stiffness are well known parameters that have significant influences for generation stick-slip motion of creep groan, effect of surface roughness has not been quite understood. One of the causes is that investigation of surface roughness is difficult to be conducted using real brake system or brake dynamometer.

Using newly proposed caliper-slider experimental model, the effect of surface roughness for the occurrence and non occurrence of stick-slip motion of creep groan has been clarified. The results show that the stick-slip motions do not established when the surfaces are relatively rough. Based on these results, it is confirmed that surface roughness is an effective parameter to control the generation of stick-slip motion of creep groan.

Chapter 4 Effect of Contact Stiffness for Stick-slip Generation

In literatures, creep groan stick-slip motion generation is generally related to two parameters, namely difference between static and kinetic friction $\Delta\mu(=\mu_s - \mu_k)$ and stiffness of the strut structure. However, both of the parameters have been not effective in controlling creep groan generation because of limitation in changing the strut stiffness and inability to control the value of $\Delta\mu$. The ineffectiveness of $\Delta\mu$ parameter is also confirmed in this analysis. It is found that stick-slip motion can also generate with low value of $\Delta\mu$, particularly when structure stiffness is low. However, stick-slip generation can be controlled by changing the roughness of the contact interfaces. Here, the effect of surface roughness is best explained using parameter of contact stiffness because the stiffness at contact interfaces is defined by the topography of the contact interfaces besides normal force, contact area, and material properties of the components. In this study, it is found that contact stiffness has a significant effect for the generation of low-frequency stick-slip motion. It is found that the power spectral densities of the generated peak frequency of the stick-slip motion increase with the increase of contact stiffness value. It is also found that the minimum contact stiffness value for stick-slip occurrence is about 10 MN/m. Thus, contact stiffness of 10 MN/m can be set as the maximum contact stiffness value for stick-slip absence, providing a benchmark for preventing stick-slip motion this experimental model.

Chapter 5 Theoretical Model of Low-frequency Stick-slip Motion

A 2-DOF dyanamic model for low-frequency stick-slip model analysis that includes contact stiffness parameter has been proposed. In the model, contact asperities are represented by damping coefficient C_{CT} and spring having stiffness K_{CT} in tangential direction, i.e. in direction of sliding. The occurrence of stick-slip motion on the 2-DOF model was simulated and the resulted phase diagram showing the occurrence and non occurrence of stick-slip motion on the dynamic model has been constructed. The phase diagram is constructed using two dimensionless parameters, namely low-frequency stick-slip *Ls* index and stiffness ratio *Sr*. The system shows stick-slip condition when the value of both *Ls* index and *Sr* ratio is relatively small. The dimensionless parameters are expressed as follows:

$$Sr = \frac{K_S}{K_{CT}} \quad \text{and} \quad Ls = \frac{\sqrt{K_S m_2}}{(\mu_s - \mu_k)W} V$$

where K_{CT} is tangential contact stiffness, N/m, Ks is the structure stiffness, N/m, $(\mu_s - \mu_k)$ is the difference between static and kinetic coefficient of friction, V is the sliding velocity, m/s, W is the normal load, N, and m is the mass, kg.

Chapter 6 Construction of Low-frequency Stick-slip Map: Creep Groan Map

A map showing necessary condition for generation of low-frequency stick-slip the experimental model has been constructed, namely creep groan map (Fig. 2), as the final result of this study. The map presents a general overview of the generating mechanism of creep groan and provides necessary information for avoiding the stick-slip generation on the experimental model. It also summarizes all data both from experiment and analytical model and constructed using two dimensionless parameters of *Ls* index and stiffness ratio *Sr*. The dynamics aspect of this map is represented by parameters of system's stiffness Ks, and the tribological aspect are represented by parameter of tangential contact stiffness K_{CT}. The boundary condition of the map is proposed using the values of *Ls* index and stiffness ratio *Sr*. Creep groan generates at conditions where *Ls* index is smaller than 400 or *Sr* ratio is smaller than 40. A new concept for avoiding creep groan generation on brake system has been proposed based on the boundary condition of the newly constructed creep groan map. Using dimensionless parameters of *Ls* index and stiffness ratio *Sr*, creep groan generation can be avoided if one of the following condition is fulfilled, i.e.

$$L_s\left(=\frac{\sqrt{m_1K_S}}{(\mu_s-\mu_k)W}V\right)>400 \text{ or } S_r\left(=\frac{K_{CT}}{K_S}\right)>40$$

Chapter 7 Conclusions

The fundamental generating mechanism of stick-slip motion of creep groan has been proposed in this thesis. The study was conducted using a newly proposed caliper-slider experimental model, designed based on similar operating principle behind a brake system. As the result of the study, a new design concept for avoiding stick-slip of creep groan has been obtained.

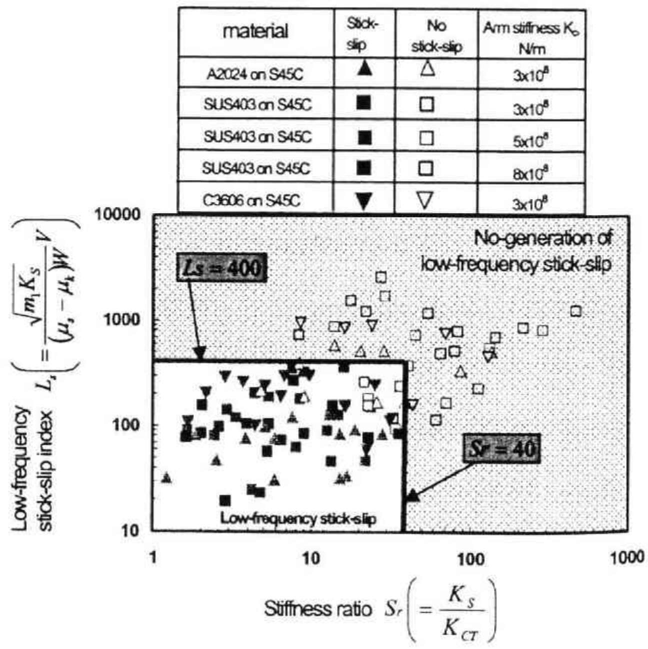

Fig. 2 Creep groan map

論文審査結果の要旨

ブレーキの鳴きは，摩擦により励起される振動に起因するものであり，静粛性，快適性が強く求められる昨今の自動車において，その制御は重要な技術課題である。なかでもオートマチック車のスタート時（ブレーキ解除時）に発生する低周波型スティックスリップに起因した騒音（クリープグローン）は，従来のダイナモシステムでは再現が困難であるため，その発生機構に関する研究は僅かしかなされておらず，その制御は経験によるところが多い。

このような背景のもとに本研究は，低周波型スティックスリップを再現できるモデル試験機を開発し，摩擦部の接触面剛性がその発生を支配する因子であることを実験により明らかにした。さらに摩擦部の接触面剛性を考慮した摩擦振動モデルの解析をもとに導出した 2 つ無次元数により低周波型スティックスリップ（クリープグローン）の発生条件を定量的に説明できることを明らかにした。本論文は，これらの研究成果をまとめたものであり，全編 7 章からなる。

第 1 章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，ブレーキの基本構成を模擬したキャリパ・スライダモデル実験装置を設計試作し，実機で発生する低周波型スティックスリップの再現が可能であることを実ブレーキ材料において実証している。これはクリープグローン発生機構を研究する上において有益な成果である。

第 3 章では，従来周知であるシステムの剛性に加え，ブレーキとして摩擦するスライダ表面の粗さ，スライダのすべり開始時の荷重及び摩擦材の機械的特性が低周波型スティックスリップの発生に強く影響することを世界で初めて明らかにしている。これは，クリープグローンの発生機構を理解するために有効かつ非常に重要な知見である。

第 4 章では，第 3 章において低周波型スティックスリップの発生に強く影響することが明らかにされたスライダの表面粗さ，荷重及び摩擦材の機械的特性を統一的に整理する「接触面剛性」を接触面の確率論を用いて導出している。さらに，その接触面剛性の増加に伴い低周波型スティックスリップの振動強度が増加することを定量的に明らかにしている。 これは，クリープグローンの発生機構のモデルを確立する上で極めて重要な知見である。

第 5 章では，接触面剛性を考慮した摩擦振動モデルを新たに提案し，その解析により導出される 2 つの無次元数「接触面剛性とシステム剛性の比」及び「摩擦係数，システムの剛性，すべり速度，スライダ質量から構成される低周波型スティックスリップインデックス」により低周波型スティックスリップの発生条件を明示できることを明らかにしている。これは，クリープグローンの発生条件を確立する手法として有効であり，学術的貢献が非常に大である。

第 6 章では，第 5 章において導出された 2 つの無次元数を両軸としたクリープグローンマップにより第 3 章おいて得られた総ての実験における低周波型スティックスリップの発生領域を定量的に示せ得ることを明らかにしている。さらにこのクリープグローンマップにもとづき低周波型スティックスリップの定量的抑制条件を明らかにしている。これはクリープグローンを抑制するブレーキシステム開発のために重要な成果である。

第 7 章は結論である。

以上要するに本論文は，低周波型スティックスリップの発生機構を明らかにするために，実機の現象を再現できるモデル試験機を開発し，摩擦部の接触面剛性がその発生を支配する因子であることを世界で初めて明らかにするとともに，低周波型スティックスリップの定量的発生条件を求め，クリープグローンを抑制するブレーキーシステムに対する設計指針を提案したものであり，機械システムデザイン工学およびトライボロジーの発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。